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Safety Analysis of the D0 High Voltage System

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First, some background in the physiology of shock hazards. The shock hazard is independent of voltage; it is only dependent on the current. Thus, a 5 KV supply delivering 1 mA is no more dangerous than a 50 volt supply delivering the same current. All that is required is sufficient voltage to drive the current through the resistance of the body. Data indicate[1] that the median sensation threshold for a sample of 167 adult men to be 1.086 mA. At currents up to 3 mA there is only a mild sensation and currents up to 10 mA are painful but not dangerous[2]. The paralysis threshold where one cannot let go of a circuit is taken to be 10 mA.

Shocks are dangerous to life when they cause ventricular filibration. The current where this occurs for 0.5% of the population is 75 mA DC. This is not the entire story for people can sustain much higher currents for short periods of time. Data show that the danger from momentary current pulses is proportional to I^2t where I is the current in amps and t is the time in seconds that the current is flowing[3]. Ref 3 indicates that the maximum safe value of I^2t for a 150 pound man is 0.027. Ref 3 also indicates that the body internal resistance is between 200 and 1000 ohms.

The normal maximum current from the D0 supply is 1 mA for the 5.6 KV supply and 3 mA for the 2 KV supply. Shorting any supply with a 1 K ohm resistor (representing the human body) causes the over current trip to trip immediately. If the over current trip circuit is disabled and the supply shorted with a 1 K resistor, the supply trips on overvoltage. The measured voltage across the 1 K resistor for several different supplies ranged from 8.6 volts to 39 volts so this is clearly not an overvoltage condition. What happens is that even with the current trip disabled, there is a 4.65 K resistor between the low side of the transformer and ground. All current must flow through this resistor so when the supply is delivering a lot of current, the

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[1]Dalziel, Charles F., "Electric Shock Hazard", *IEEE Spectrum*, Feb, 1972.

[2]Lee, Ralph H., "Electrical Safety in Industrial Plants", *IEEE Spectrum*, June, 1971.

[3]Kleronomos, Chris C. and Cantwell, Edward C.,"A Practical Approach to Establish Effective Grounding for Personnel Protection", IEEE Conference Record Paper, CH460-5/79/0000-49, 1979.

transformer is forced below ground potential which in turn forces the voltage readback to the comparator to go negative. The comparator's normal operating voltage is from -0.3 to 36 volts so when it sees a negative voltage less than 0.3 volts, it trips. This trip works on all 3 supply types. The typical trip time is around 200 mS. Using a conservative value of current as 50 mA and a trip time of 250 mS gives $I^2t = 6.25\ 10^{-4}$. Dividing this into 0.027 gives a safety factor of 43. While these currents can cause a painful sensation, they are not at all dangerous. Note that this involves a double failure - a failed current trip circuit and a person touching a high voltage lead.

A second area of concern is the stored charge. This is what normally causes the painful sensation when one touches a high voltage supply. Even small capacitances can deliver substantial amounts of current through the low resistance of the human body. Since this is a pulsed shock, one can calculate I^2t for this case. The current from a capacitor is

$$I = \frac{V0}{R} \exp[-\frac{t}{RC}]$$

where V0 is the applied voltage, R is the discharging resistance and C is the capacitance. Since I is a function of time we compute I^2t by integrating I^2dt from 0 to ∞ This gives

$$I^2t = \frac{V0^2\ C}{2\ R}$$

For V0 = 5.6 KV, C= 3 nF and R= 200 Ohms (lower limit of body resistance) we get $I^2t = 2.35\ 10^{-4}$. Adding the supply value from above to this gives $8.55\ 10^{-4}$. Dividing this result into the maximum safe value for this quantity (0.027) gives a safety factor 32. One must increase the capacitance by a factor of 100 before approaching the lower limit of the a health hazard. Again, this is the safety factor with a failure in the current trip circuit. With no failures. the value of $I^2t = 2.35\ 10^{-4}$ and the safety factor is 115. The 3 nF capacitance is the output filter capacitor. The other 3 nF capacitors have 100 K resistors in the current path so they make a negligible contribution to I^2t.

How does this shock hazard compare with our everyday experience? A good example is the shock from walking on a carpeted floor and then touching a door knob. The voltage that can develop is a function of many things including the humidity and the carpet resistance. The maximum voltage that can be developed is around 20 KV and the capacitance of a human is about 120 pF[4]. Putting these values into the above formula for I^2t gives $I^2t = 1.2\ 10^{-4}$ which is about one half of the value for the power supply with no failures. In other words the maximum shock from a normal power supply is about twice as large as the maximum shock from walking on a carpet.

When the supplies are connected to long cable runs, the danger from the charge stored in the cable increases greatly. The D0 high voltage cable has a capacitance of 30 pF/foot. Cable lengths of 135 feet are used throughout the detector. In the worst cased a single supply feeds up to 20 cables through two levels of fanout. Twenty 135 foot cables gives a capacitance of 81 nF or 27 times the supply capacitance. This reduces the safety factor from 115 to 4 which is still safe. This safety factor is for the maximum supply voltage (5600 V). The detector usually runs at 2500 V and the maximum allowed voltage (voltage limit pot on the HV supply) is 3000 V. Since the shock hazard goes as V^2, this increases the safety margin by a factor of 4 giving a total safety margin of 16. Note that the contribution from a failed current trip is small (10%) compared to the cable capacitance for this case.

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Safety analysis looks OK. There is no apparent electrocution hazard. Also, as an extra precaution the equipment is housed in grounded metal enclosures and all HV is transported via shielded cables (coax) with the shield connected to ground.

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[4]Digital Equipment Corporation, "Installation Guide for Computer Systems".